

Size-structure and growth of individuals suggest high exploitation rates in the fishery for blacklip abalone, *Haliotis rubra*, in New South Wales, Australia

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Abstract

The proportion of recent recruits in the catch of the NSW abalone fishery was estimated by combining information on growth rate and the size-structure of the commercial catch. Growth rates of individuals around the minimum length limit of 115 mm suggest most individuals less than 125 mm recruited to the fishery in the last year. These individuals make up between 50% and 95% of the commercial catch in all zones of the fishery. This dominance of recent recruits in the catch of the fishery makes monitoring of the abundance of pre-recruits, to provide information on likely fluctuations in recruitment, particularly important to management. Growth rates of individuals below the minimum length limit of 115 mm suggest most individuals above 100 mm will recruit to the fishery in the next year. Monitoring over the last four years has found no significant decline in the relative abundance of these pre-recruits in six major regions of the fishery. The high exploitation rate, suggested by the combination of patterns in growth and the proportion of recruits in the catch, combines with several other factors to make the NSW abalone fishery very different from those for the same species in other states in Australia.

Introduction

The recruitment of new individuals is one of the most important processes determining the dynamics of many marine populations (Underwood and Fairweather 1989). In populations exposed to fishing, two types of recruitment are often defined. Individuals can recruit to the population following settlement and metamorphosis (here referred to as settlement), and subsequently, as they grow, individuals can recruit to a fishery (here referred to as recruitment). Settlement and recruitment of many species varies greatly in time and space, and as this variation can have important consequences for the dynamics of the population, it can also have important consequences for management of any associated fishery (e.g. Shepherd and Partington 1995). Because a range of processes can operate to alter the patterns apparent at settlement (e.g. McShane 1991), the abundance of individuals immediately prior to recruitment is potentially much more important to management of a fishery.

The importance of variation in recruitment to a fishery is influenced by the size of the stock already recruited. For example, variation in recruitment becomes crucial when the fishery is dominated by new recruits (e.g. some species of prawn, Garcia and Le Reste 1981). Variation in recruitment becomes less important when the population available to the fishery is made up of a large number of accumulated age-classes that dominate the new recruitment (e.g. orange roughy, Mace *et al.* 1990). Populations of abalone are often portrayed as being dominated by an accumulation of large, old individuals (e.g. Sainsbury 1982, Breen 1986, Tegner *et al.* 1989, Nash 1992). These accumulations can be particularly vulnerable to fishing (Davis *et al.* 1996), and their depletion can lead to local settlement and recruitment failures and further decline in the population (Shepherd and Partington 1995).

In this paper we describe the apparent importance of recruitment to the New South Wales (NSW)

abalone fishery. We do this by combining information on the growth rates of pre-recruits (i.e. defined as those individuals that will recruit to the fishery within the next year) and recruits (i.e. defined as those individuals that have recruited to the fishery in the last year), with information on the length-structure of the commercial catch. These data indicate that the NSW abalone fishery is dominated by individuals that have recently recruited to the fishery. As a consequence, monitoring of the relative abundance of pre-recruits is likely to provide information on future recruitment, and hence the abundance of abalone available to the fishery. Finally, we compare the importance of recruitment to the fishery in NSW with its importance in fisheries for the same species in the more southern states of Victoria and Tasmania (Figure 1). It appears that differences among the states in the biology and ecology of abalone, the behaviour of commercial divers, and patterns of management have led to very different fisheries.

The commercial fishery for abalone (*Haliotis rubra*) in NSW is currently limited to a Total Allowable Commercial Catch (TACC) of 333 t. This is substantially lower than fisheries for the same species in Victoria (over 1500 t) and Tasmania (over 3000 t). In addition, there are also differences in the minimum length limit among the states. In NSW, there is a single length limit of 115 mm, whilst in the other states several different length limits are enforced. In Victoria most abalone are caught using a 120 mm length limit, whilst in Tasmania most are caught using a 132 mm length limit (see Prince and Shepherd 1992 for other differences in management among the states). In general, in each state commercial divers use trailable boats to gain access to sites. Fishing effort at a site is determined by a range of factors including its distance from a boat ramp, weather conditions and expected catch rates. Once at a site, divers will search an area of reef and collect most of the abalone they encounter over the length limit. Catch rates in NSW (about 20 kg.hr⁻¹) are much lower than in the southern states (above 50 kg.hr⁻¹), due mainly to the additional time required to find abalone above the length limit.

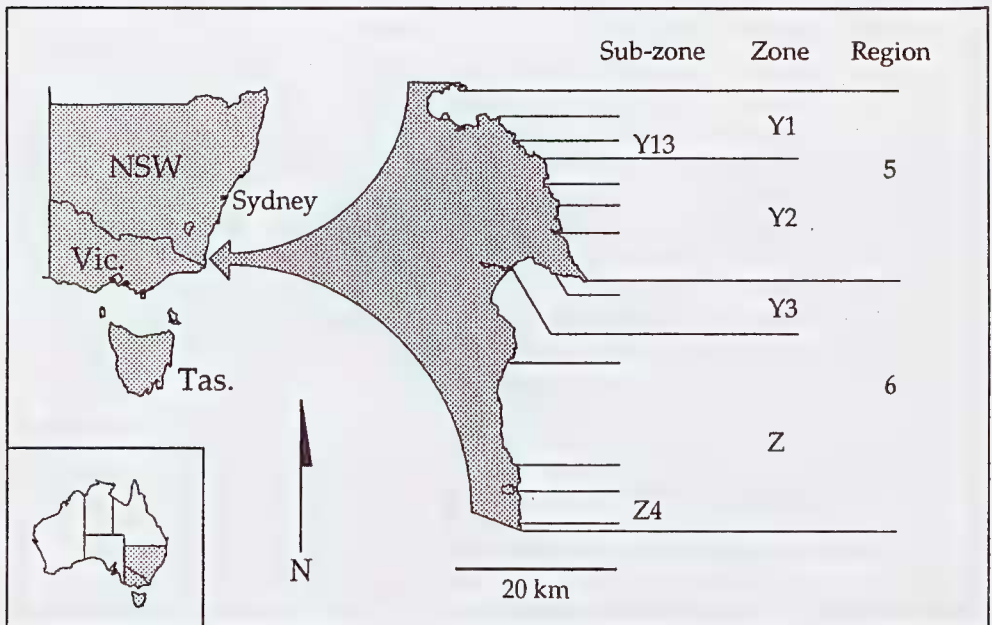


Figure 1. Map of Australia (inset) showing states of New South Wales (NSW), Victoria (Vic.) and Tasmania (Tas.), with section of NSW coast showing sub-zones, zones and regions described in text.

Materials and methods

Growth of pre-recruits and recruits

Estimates of growth were derived from the tagging data set described in Worthington *et al.* (1995). Briefly, maximum likelihood was used to fit a model containing up to six parameters to the length-increment data. One of the parameters described the coefficient of variation in growth among individuals (see Francis 1995). This allowed estimates of the expected growth, and its confidence intervals, for an individual of a given length. For example, at one site (Eden II) the expected annual growth of a 90 mm abalone was 19.9 mm and the 95% confidence interval was between 4 mm and 35 mm. In other words, 95% of 90 mm abalone would be expected to be between 94 mm and 125 mm one year later.

Estimates of growth and its variation can also be expressed in terms of the proportion of individuals expected to reach a given length. In the example above, about 25% of 90 mm abalone will grow more than 25 mm in a year and enter the fishery. This allows the calculation of the proportion of abalone of a given length that will enter the fishery within one year. As estimates of growth and variation in growth among individuals will vary among sites (Worthington *et al.* 1995), we have calculated the percentage of individuals of a given length that will grow to ≥ 115 mm and enter the fishery within the next year for both a fast and a slow growth site (Eden I and Eden II in Worthington *et al.* 1995). In addition, we have calculated the proportion of individuals of a given length that will grow to ≥ 125 mm within the next year. Rates of growth suggest that most individuals ≥ 125 mm would have been recruited to the fishery for more than one year (see later).

Size-structure of the commercial catch

Estimates of the size-structure of the commercial catch were gained by measuring a sample of abalone from a subset of the daily catches collected by commercial divers. When logistically possible an abalone processor is visited, and for all divers and days available, the shell length, width and total weight of a sample of abalone were measured to the nearest mm or 5 g. Only one bin (about 50–100 individuals) per diver per day is sampled. This sampling design was chosen because the size-structure of abalone in different bins from the same diver on the same day is more similar than between bins from the same diver on a different day or among different divers (Andrew and Chen 1997). The sampling of only 50–100 abalone per diver per day allowed us to sample approximately 100 diver-days out of a total of about 3000. This sampling design should provide a precise estimate of the size-structure of the commercial catch (Andrew and Chen 1997).

The size-structure of the commercial catch has been estimated in this way for each year since 1993, and some comparable estimates are available from earlier years. The comparison among years is complicated by differences in the minimum length limit. A minimum length limit was first introduced in 1973 (100 mm) and was increased in 1980 (108 mm), 1986 (111 mm) and 1987 (115 mm). Since 1993, estimates of size-structure are available for six regions in the fishery which are used for stock assessment purposes (Figure 1). Estimates are also available for a selection of zones and sub-zones in the fishery (Figure 1). These smaller spatial divisions are used for the reporting of daily catch and effort statistics by the commercial divers, and represent the smallest possible scale for management that is currently available.

Relative abundance of pre-recruits

During surveys of the relative abundance of abalone at fixed sites spread along the NSW coast, estimates of the size-structure of the populations were also collected. These surveys were started in 1994 and have been repeated in 1995 and 1996 between June and December each year. At more than 40 sites, all abalone encountered were gathered by carefully searching all caves, crevices and boulders within an area of about 20 x 20 m until a sample of approximately 100 was collected. No boulders were over-turned during this process. The abalone were brought to the surface where the shell length and width of each were measured to the nearest mm. Abalone were then returned to the water, and placed by hand in the area from which they were collected. Only the relative frequency of individuals >90 mm in length is shown here, as few individuals below this size can be considered pre-recruits.

Results

Growth of pre-recruits and recruits

Rates of growth differ considerably among sites within NSW (Worthington *et al.* 1995). This is reflected in the proportion of abalone of a given length entering the fishery within one year (Figure 2). For example, at sites where individuals grow quickly, more than 50% of 100 mm abalone are pre-recruits, and more than 25% of 90 mm abalone are pre-recruits. In contrast, less than 15% of 100 mm abalone are pre-recruits at sites where they grow slowly, and it is not until almost 110 mm that more than 50% of individuals are pre-recruits. Because more individuals are collected from sites where the abalone grow quickly (see Worthington and Andrew 1997), it is likely that the average proportion of pre-recruits at a length is more closely related to that at sites where individuals grow quickly rather than sites where they grow more slowly.

Variation in growth among sites is also reflected in the proportion of individuals growing to ≥ 125 mm within one year (Figure 2). Less than 10% of 90 mm individuals will grow to ≥ 125 mm at both fast and

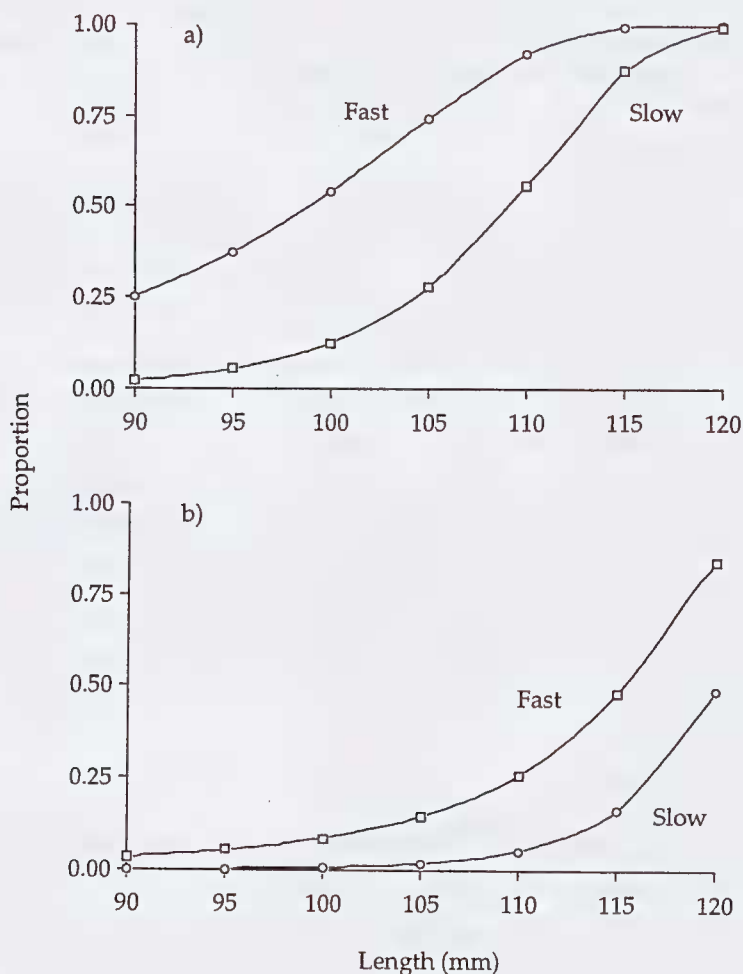


Figure 2. Proportion of abalone reaching a) 115 mm in length and b) the length-classes in the fishery >125 mm, after one year plotted against their starting length for a fast and slow growth site.

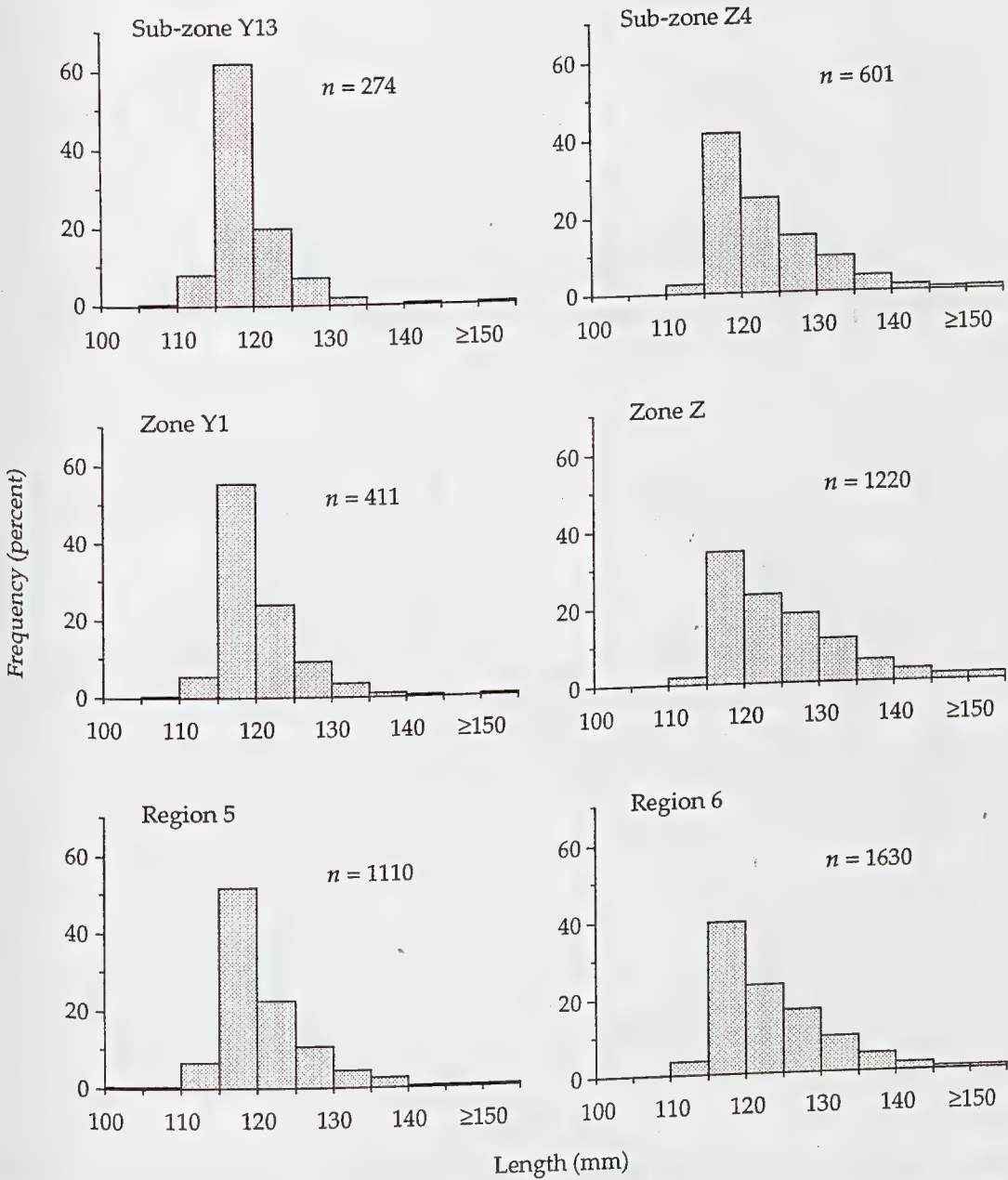


Figure 3. Length distribution of the commercial catch of abalone during 1996 from sub-zones Y13 and Z4, zones Y1 and Z, and regions 5 and 6. Sample sizes are also shown.

slow growth sites. Even by 120 mm, only 50% of individuals will reach 125 mm within one year at sites where they grow slowly. For 115 mm abalone, about 50% of individuals at fast growth sites, and 20% of individuals at slow growth sites, will reach 125 mm within one year.

Size-structure of the commercial catch

During 1996, there was significant spatial variation in the size-structure of the commercial catch at

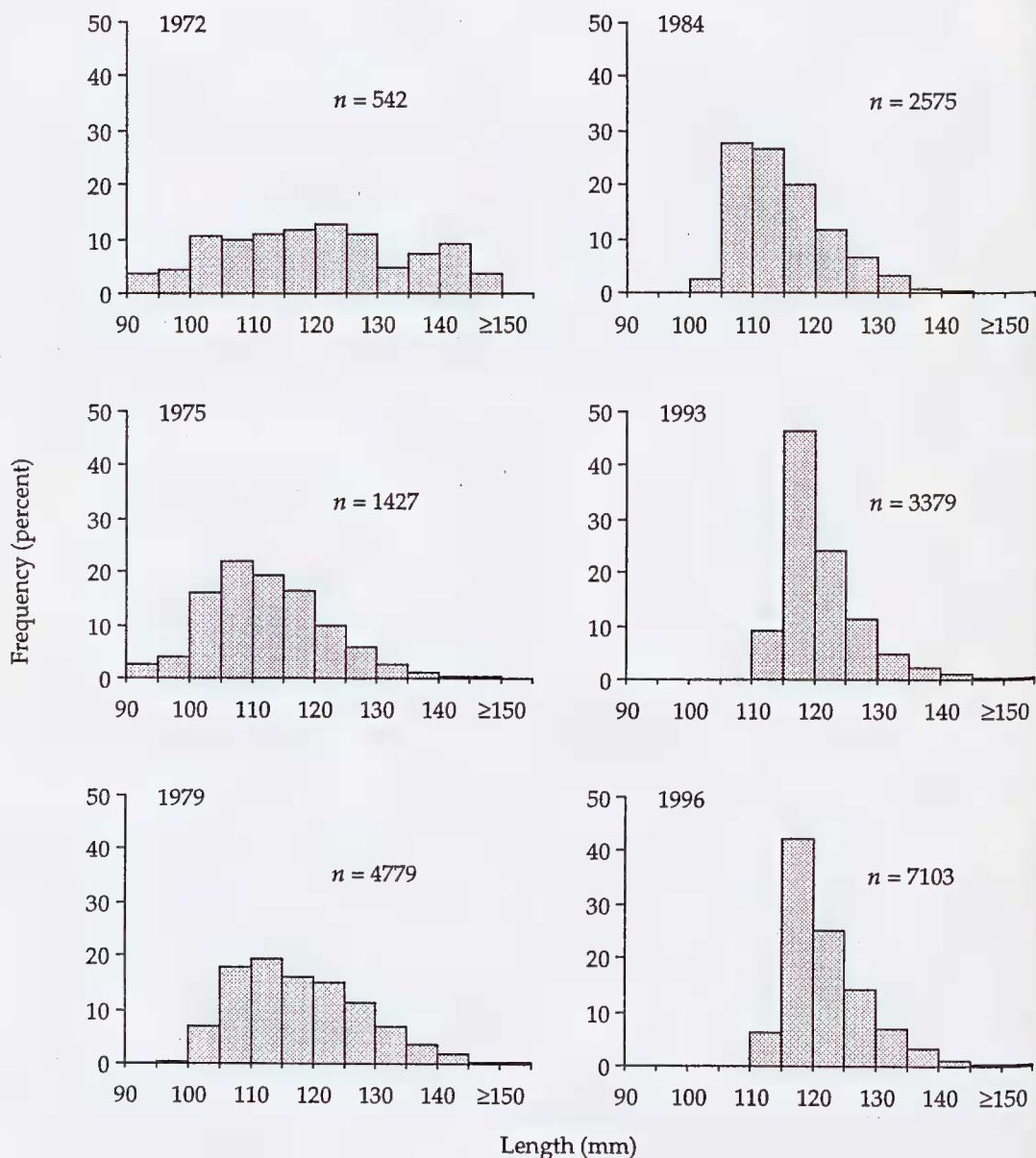


Figure 4. Length distribution of the commercial catch of abalone in NSW during several years. Note, there was no restriction on the minimum length of abalone during 1972, but a 100 mm length limit was enforced in 1975 and 1979, 108 mm in 1984, and 115 mm in 1993 and 1996. Sample sizes are also shown.

a range of spatial scales. While the distributions declined relatively smoothly away from the minimum length limit in all samples, there were differences in the rate of this decline. For example, there was a steep decline (slope of regression ($\pm$ s.e.) = 0.18 ± 0.04) in the length-distribution from sub-zone Y13 (Figure 3), and most individuals caught were relatively close to the length limit (Figure 3). Over 90% of individuals caught in sub-zone Y13 were <125 mm in length. In contrast, the distribution from sub-zone Z4 (Figure 1) was comparatively flat (slope of exponential decline = 0.12 ± 0.01), and only 68%

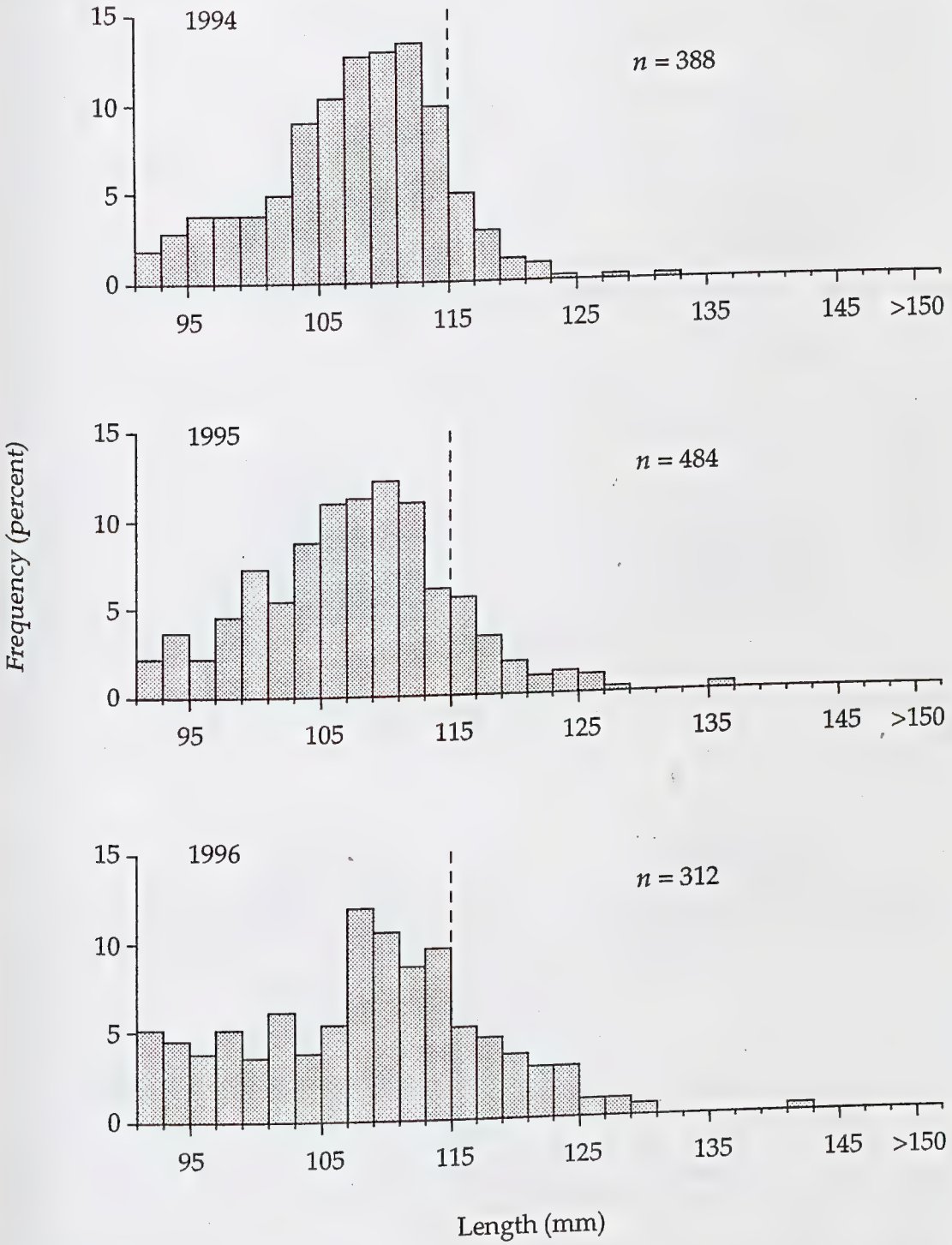


Figure 5. Length distribution of abalone populations during 1994, 1995 and 1996 in region 4. Sample sizes are also shown.

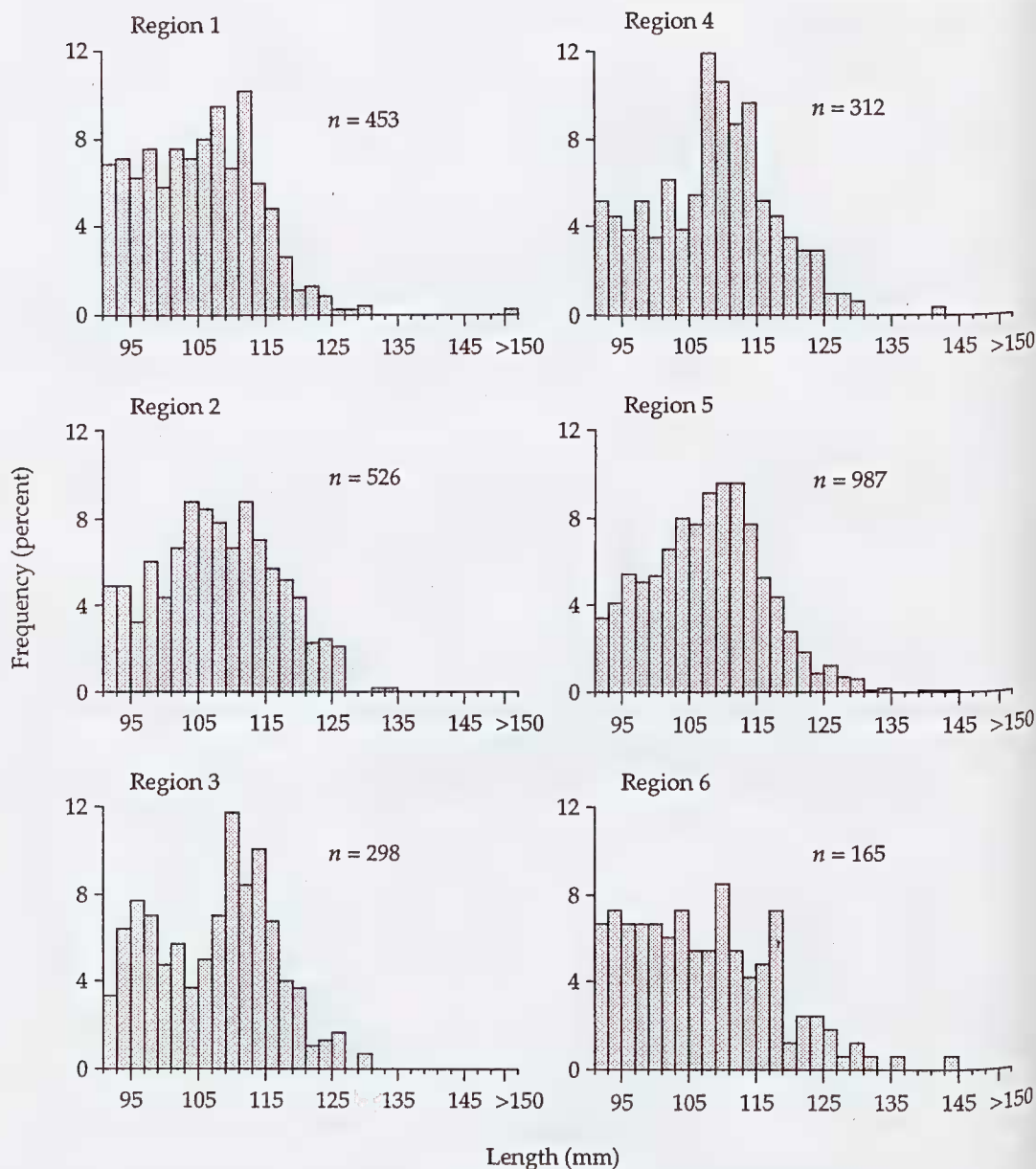


Figure 6. Length distribution of abalone populations during 1996 in each of six regions. Sample sizes are also shown.

of individuals were below 125 mm in length (Figure 3). At the larger spatial scales of zone and region, similar patterns were also evident. More larger individuals were caught in zone Z and region 6 than in zone Y1 and region 5 (Figure 3). In region 5, over 80% of individuals caught were <125 mm, whilst in region 6 this dropped to 65%.

During the last four years, there has been a small decline in the proportion of individuals <125 mm in the catch of the whole fishery. For example, during 1993 80% of individuals were <125 mm in length, whilst in 1996 this dropped to 74% (Figure 4). This reduction is likely to represent a significant change

in the length structure of the population (Andrew and Chen 1997). The proportion of individuals in these length-classes during the last four years is much larger than in previous years, although this comparison is complicated by differences in the minimum length limit. For example, during 1972 there was no minimum length, and individuals were much more evenly spread among the length-classes above 90 mm (Figure 4). During 1975 and 1979, a 100 mm minimum length limit was enforced and individuals were less evenly distributed among the length-classes, but the length-class immediately above the limit was not the most common in the catch (Figure 4). During 1984, when a 108 mm length limit was being enforced, individuals were still more evenly spread among the length-classes than in the last four years (Figure 4).

Relative abundance of pre-recruits

Patterns in the size-structure of abalone in the population were consistent with relatively fast rates of growth. For example, in region 4 during 1994 only 11% of individuals >90 mm in length were also =115 mm, and hence already recruited to the fishery (Figure 5). Individuals between 105 mm and 114 mm were relatively abundant. By 1996, the proportion of individuals immediately below the length limit had declined, and over 22% of individuals >90 mm in length had recruited to the fishery at that time. That is, the strong cohorts of pre-recruits seen in 1994 and 1995 had recruited to the fishery in 1996, and led to a large increase in the proportion of individuals available to the fishery. This is supported by both observed increases in the catch rate of commercial divers, and in the abundance of individuals =115 mm in the independent surveys (Andrew *et al.* 1996).

Spatial variation in the relative abundance of pre-recruits is likely to be reflected in future patterns in catches. For example, in region 6 during 1996, 24% of individuals >90 mm were already recruited to the fishery, and relatively few individuals were immediately below the length limit (Figure 6). In contrast, in region 3 during 1996, there were comparatively few individuals already recruited to the fishery (19%), but two strong cohorts were present immediately below the length limit (Figure 6). Abundances of individuals <115 mm have also increased over the last two years of the independent survey in this region. Many of these individuals are likely to recruit to the fishery in the next year. In contrast, in region 1 during 1996 only 12% of individuals >90 mm were available to the fishery (Figure 6), and abundances of individuals <115 mm had declined in the independent surveys. Recruitment to this region over the next year is likely to be lower than all other regions.

Discussion

Recruitment to the NSW abalone fishery

A large proportion of individuals caught in the NSW abalone fishery have recruited within the last year. This proportion appears, however, to vary in space within the fishery, and is related to variation in demographic factors such as patterns of settlement, growth and mortality. When strong year-classes grow quickly and become available to the fishery in zones where few individuals are already above the length limit, up to 95% of the commercial catch can be <125 mm in length. In other zones with lower exploitation rates and more larger individuals, individuals in these length-classes can still often represent over 40% of the commercial catch (Andrew and Chen 1997). In much smaller areas (i.e. <1 km) within some sub-zones, slow growing, stunted populations exist (Worthington *et al.* 1995) that are dominated by accumulations of old abalone. Recent recruits are likely to represent a small proportion of the catch from these populations. Total catches from such slow growing populations are small, and populations that grow faster dominate the catch (see Worthington and Andrew 1997 for further discussion of the relationship between growth rate, frequency of fishing and total catch). Across the whole fishery, more than 70% of the total catch has been <125 mm in length over the last four years. Estimates of growth suggest most of these individuals have recruited to the fishery within the last year.

The proportion of recruits in a fishery is not only determined by demographic factors controlling the number of recruits, but also by factors affecting the individuals already available to the fishery. Perhaps

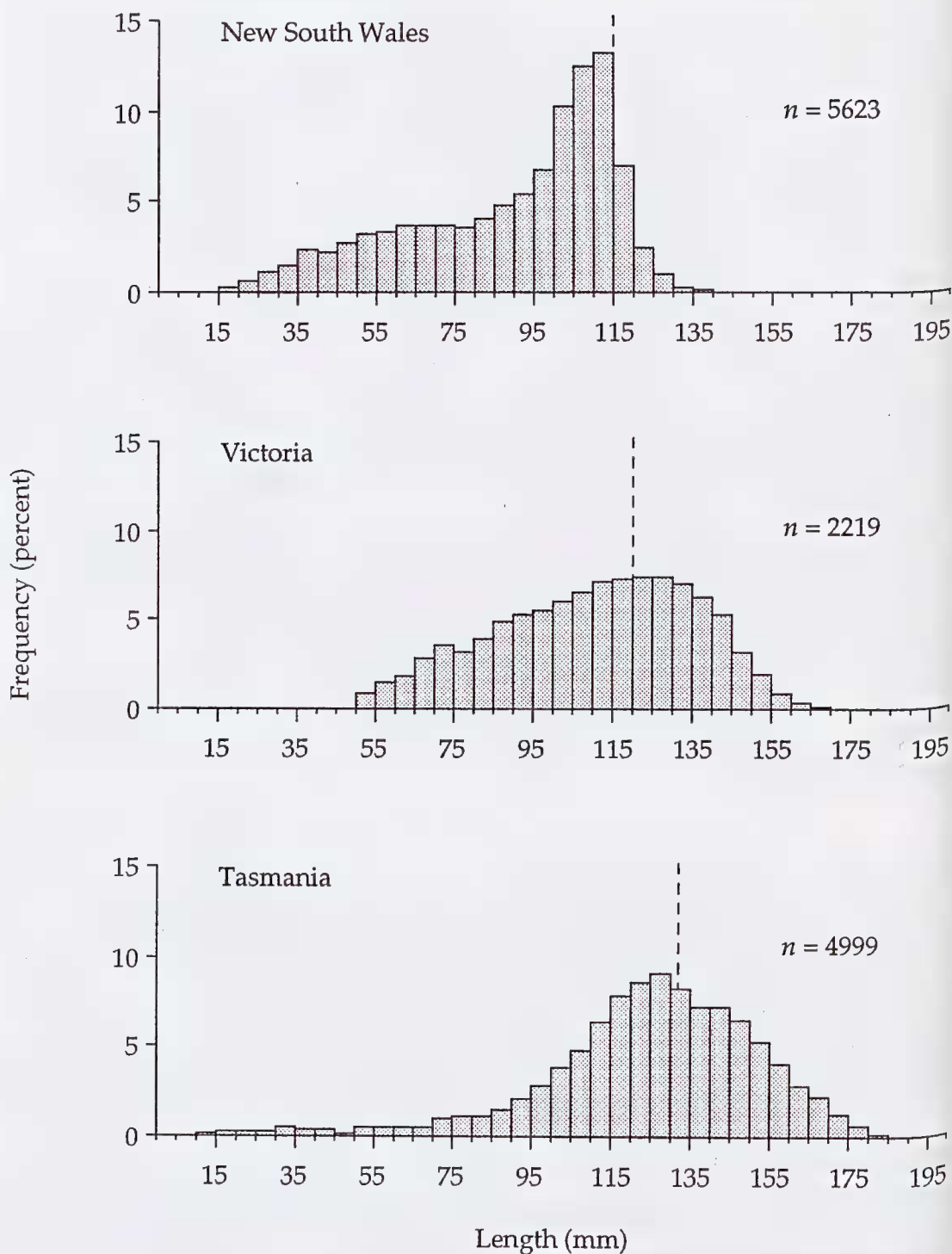


Figure 7. Length distribution of abalone populations during 1995 in New South Wales, Victoria and Tasmania. Sample sizes are also shown.

the most important of these include the effects of fishing and changes in the minimum length limit. The extent to which these factors are responsible for the large number of recruits in the NSW abalone fishery is unclear. Historic changes in the minimum length limit have certainly been responsible for changes in the number of individuals available to the fishery. This has been clearest following the large increases of the length limit in 1980 (100–108 mm) and 1986–1987 (108–111–115 mm). The effects of fishing on the number of recruited individuals, and hence the proportion of recruits in the fishery, is less clear. Possible trends are suggested by comparing the current size-structure with that from earlier in the fishery's development. Such comparisons suggest that there has been a significant change in the size-structure of the population. Perhaps most importantly, this suggests the accumulated stock of old, large abalone has been seriously depleted over the life of the fishery. It is important to note, however, that small increments in the minimum legal size limit over this period will complicate interpretation of these trends. Such a depletion is also supported by a comparison of the length-structure of abalone in NSW with those in Victoria and Tasmania where there are many more large (>125 mm) abalone (Figure 7). Consequently, it appears that the domination of recent recruits in the catch of the NSW abalone fishery is at least partly caused by a high exploitation rate.

The large proportion of recruits in the catch of the abalone fishery in NSW has several important consequences. Perhaps most importantly, it suggests that the fishery is no longer supported by an accumulation of large abalone. Rather, it is heavily reliant on the growth and recruitment of new individuals each year. This makes the fishery more vulnerable to failure in recruitment, as there is no opportunity for its effects to be dissipated by an accumulated biomass of larger individuals. Such a pattern has preceded further declines in several other abalone fisheries (e.g. Tegner *et al.* 1989). In contrast, in NSW indices of biomass, abundance and size-structure have been increasing over each of the last four years.

Potential for monitoring pre-recruits

The large proportion of recruits in the NSW abalone fishery also has a fortunate consequence for management. Knowledge of the abundance of pre-recruits can provide information on the likely future abundance of recruits and hence, of abalone available to the fishery. This enables more reliable forecasts of potential harvest when setting the TAC (see Walters 1989). Similar knowledge of patterns in the abundance of individuals at settlement (Nash *et al.* 1995), as pre-recruits (Farlinger and Campbell 1992) or at some intermediate age (Shepherd and Partington 1995), is used to aid management of other abalone fisheries. The ability to estimate patterns in abundance of individuals as soon as possible to when they recruit is clearly desirable, as the patterns are more likely to be modified as the intervening time increases. Current research in NSW is now concentrating on gaining a better understanding of these processes in the early life-history of abalone.

A variety of different methods could be used to estimate patterns in the relative abundance of pre-recruits. The size-structure of populations is sampled in areas adjacent to the independent surveys, where individuals are counted in length-classes but not disturbed, so the information from the two methods can be combined. By combining the independent information within small areas we hope to provide a more reliable estimate of patterns in the abundance of pre-recruits at this scale. Further, by combining patterns in relative abundance and size-structure from several small areas, estimates of the likely recruitment of individuals within a sub-zone, zone or region can be made. When localised recruitment failures occur, there is the opportunity to prevent further collection of individuals from certain sub-zones, as has been done in several sub-zones adjacent to Sydney (Figure 1). It remains to be seen whether recruitment returns to levels comparable to those before the closure.

A comparison with fisheries in other states

We have described above some of the similarities and differences between the fisheries for *H. rubra* in NSW, Victoria and Tasmania. Rates of growth, mortality and fecundity appear largely similar among the states (see Worthington and Andrew 1997). In contrast, perhaps the most conspicuous difference between the states is the apparent exploitation rate of the fisheries, as suggested by the length-structure

of abalone that remain (Figure 7). Other differences among the states also exist, including historical changes in management, patterns in the behaviour of divers, and the existence in NSW of the large, diadematid sea urchin *Centrostephanus rodgersii* which leads to fundamental differences in ecology of the associated reef (see Andrew and Underwood 1992).

The differences among the states described above have led us to question the appropriateness of some arguments derived from research on fisheries in the other states to the fishery in NSW. For example, in NSW divers mostly launch trailable boats to gain access to sites. Boat ramps are spread evenly along the coast, so that few sites can not be accessed by a short (<30 min.) boat trip. This combines with the high exploitation rate of the fishery to ensure that most sites where abalone exist are fished very frequently (i.e. on average, every sub-zone in the fishery is visited by a commercial diver at least once per week) and relatively few abalone are above the length limit at each site. This contrasts with areas in the other states, and with the inaccessible, west coast of Tasmania in particular, where stocks of large abalone exist. As a consequence, the arguments concerning serial depletion of stocks, that have evolved in Tasmania (e.g. Harrison 1983), have less appeal in NSW. This is not to say serial depletion is not occurring in NSW. Effort from the closed sub-zones adjacent to Sydney appears to have been shifted to the most southern sub-zones where some larger abalone exist (see Zone Z in Figure 3). Rather, serial depletion of stocks is mostly occurring on a much shorter time scale, equivalent to the high rates of visitation to most sites in the fishery. As there are no areas with stocks of large abalone remaining in NSW, the minimum length limit effectively prevents the further depletion of sites. Divers then choose to visit new sites before continuing to deplete the density of abalone in already heavily fished areas. Patterns in catch and effort still need to be carefully monitored to ensure this situation does not change.

Research in other states has also been used to suggest that the catch rate of commercial divers is a poor index of change in relative abundance of abalone (e.g. Prince and Shepherd 1992). Arguments supporting this are related to several factors. These factors include the potential of serial depletion to maintain divers' catch rates while stocks decline, the ability of abalone to actively aggregate as adults, and the reduction in catch rate at very high densities related to the handling time of individual abalone. As described above, in NSW the high visitation and exploitation rates suggest to us that at the moment serial depletion is not seriously biasing catch rate as an indicator of annual changes in relative abundance. In a similar way, the results of several tagging experiments in NSW provide no support for the argument that adult *H. rubra* actively move towards each other (G. Hamer, unpublished data). Finally, problems in analysing commercial catch data related to handling time simply do not occur at the low densities of abalone and subsequent catch rates that occur in NSW. As a consequence, we believe that standardised catch rates of divers in NSW currently provide a more reliable picture of annual change in the relative abundance of abalone than in the other states. Similar arguments were also used by Geaghan and Castilla (1986) to suggest catch rates of loco in Chile are useful indicators of abundance.

We do not imply that catch rate will provide completely accurate and precise information on changes in the abundance of abalone in NSW. Rather, the NSW abalone fishery appears to present a situation where catch and effort statistics can provide useful information about the population, particularly when interpreted in conjunction with other measures. Indeed, the true worth of catch and effort can only be confirmed by comparison with an independent measure of abundance (e.g. abundances in the independent survey). These unique attributes of the NSW abalone fishery, which include the high exploitation suggested by the proportion of recruits in the catch, emphasise how different it is from fisheries for the same species in other states of Australia.

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